

When "the fog comes on little cat feet," we want to see what it's hiding. The millimeter-wave regime of the electromagnetic spectrum can show us—if we have the necessary vision.

Passive millimeter-wave imaging

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The regime of the electromagnetic spectrum where it is possible for humans to see is that part where the sun's radiance peaks: the visible regime. In that regime, the human eye responds to different wavelengths of light scattered by objects by recognizing different colors. In the absence of sunlight, however, the natural emissions from Earth objects (at 300 Kelvin) are concentrated in the infra-red (IR) regime. Advances in IR-sensor technology in the last 40 years now make night vision possible. The exploitation of the millimeter wave regime follows a natural progression in the quest to expand our vision, for the great advantage of millimeter-wave radiation is that it can be used at night, in fog, and in other poor-visibility conditions that would normally limit our ability to see.

The millimeter-wave region of the electromagnetic spectrum lies between 30 and 300 GHz, with corresponding wavelengths of 10 and 1.0 mm. It is a region that has not been widely explored for passive imaging for three main reasons: weak natural emission, hardware limitations, and poor resolving power. Objects emit millimeter-wave radiation similar to IR and visible radiation, but that radiation is weak by comparison. The product of emissivity (ϵ) and true physical temperature of an object equals its brightness (or radiometric) temperature. A perfect absorber has $\epsilon = 1$ and is known as a blackbody, as opposed to a perfect reflector, which has $\epsilon = 0$. The emissivity of an object (which is polarization-dependent) is a function of the dielectric properties of its constituents, its surface roughness, and the angle of observation. (A sample of the measured emissivities of diverse materials at various frequencies is given in the table on the next page.) The radiation intensity of a 300-Kelvin blackbody falls exponentially by about eight orders of magnitude from a peak value in the IR to the millimeter-wave regime at around 94 GHz (Figure 1). This large decrease in intensity is partially compensated for by the lower photon energy that occurs at millimeter-wave frequencies. However, this situation is dramatically reversed in fog and other inclement weather when one takes into account the signal attenuation by atmospheric constituents. Here the strength of the propagated signal peaks in the millimeter-wave region, as the figure shows.

The second reason, hardware limitations, is due to the low millimeter-wave power flux, but is not the problem it once was. Several recent technological advances have enabled the exploitation of millimeter waves. Receivers with mixer front-ends using Schottky-barrier diodes have demonstrated double-sideband noise figures of 6 to 10 dB over the 94- to 300-GHz regime,

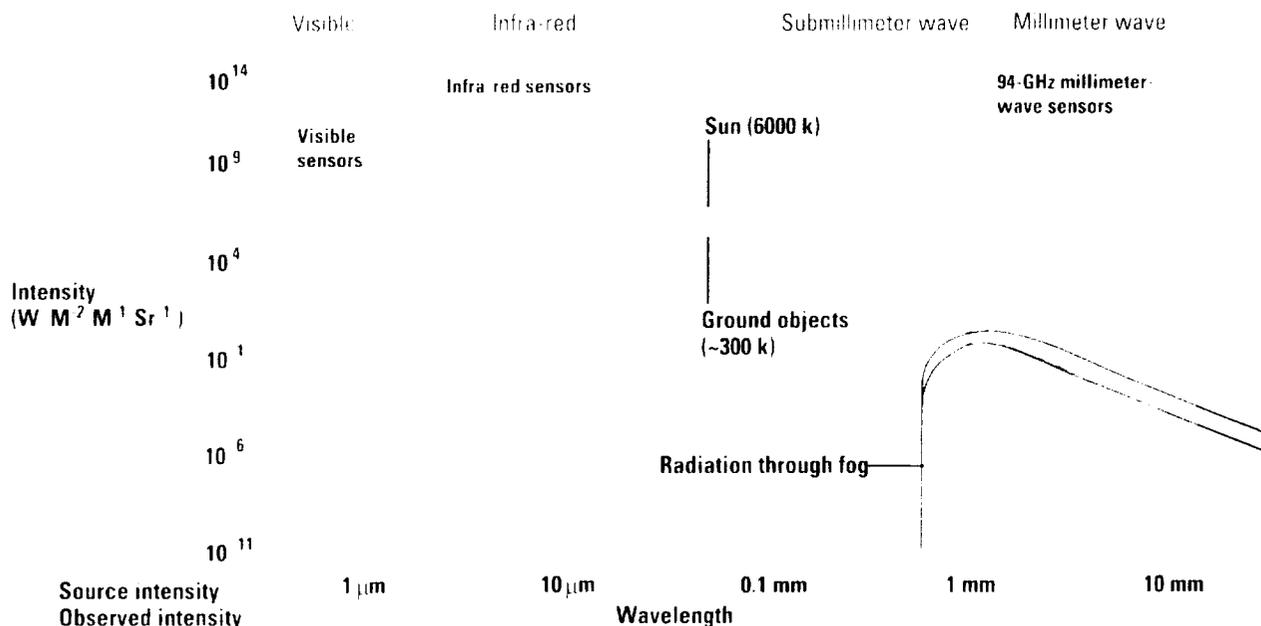
Effective emissivity for vertical look-down assuming specular reflection. The emissivity of an object (which is polarization-dependent) at a given frequency is a function of the dielectric properties of its constituents, its surface roughness, and the angle of observation

Surface	Effective Emissivity		
	44 GHz	94 GHz	140 GHz
Bare metal	0.008	0.040	0.058
Painted metal	0.034	0.098	0.122
Painted metal under canvas	0.181	0.240	0.299
Painted metal under camouflage	0.222	0.389	0.463
Dry gravel	0.879	0.921	0.957
Dry asphalt	0.891	0.914	0.941
Dry concrete	0.861	0.905	0.946
Smooth water	0.472	0.588	0.662
Rough dirt	1.0	1.0	1.0
Hard-packed dirt	1.0	1.0	1.0

which is adequate for imaging, and high-electron-mobility transistors are demonstrating a 1.9 dB noise figure with greater than 7 dB associated gain at 94 GHz. In addition, supercooled Josephson junctions operating at helium temperatures have even better performance with quantum-efficient detection. Transmission lines and antenna technologies have also kept pace, partly because of the recent interest in radio astronomy applications. The advent of Millimeter Wave Monolithic Integrated Circuit technology has also greatly increased the regime's potential: direct detection and low-noise amplification are now a reality.

The third reason, limited imaging resolution at millimeter-wave frequencies, has traditionally restricted the regime's use to short-range applications. At 3-mm wavelength, and using diffraction-limited optics with a one-meter aperture, the angular resolution is approximately 4 milliradians compared to 12 microradians in the IR region (10-micron wavelength) and 0.7-microradian in the visible region (6,000 angstroms). At a 5-km range, this translates into a passive millimeter-wave spatial resolution of 20 meters, barely adequate for discerning such landmarks as roads and buildings. From a range of 1,000 km, typical of low-Earth-orbit satellite applications, the resolution is 4 km, which again borders on the utility limit for observing mesoscale meteorological phenomena. A typical cloud, for example, is 10 km in extent and

Figure 1. The effect of fog on blackbody radiation observed at a distance of 1 km from the source



the cloud scale of interest is on the order of 100 meters. Again, the situation is changing. With the advent of long-baseline interferometry, millimeter waves need no longer be relegated to coarse-scale applications—the correlation of radiometric signals from receivers separated spatially, the so-called ‘sparse-array’ configuration, has the net effect of increasing the receiving aperture, leading to improved resolution.

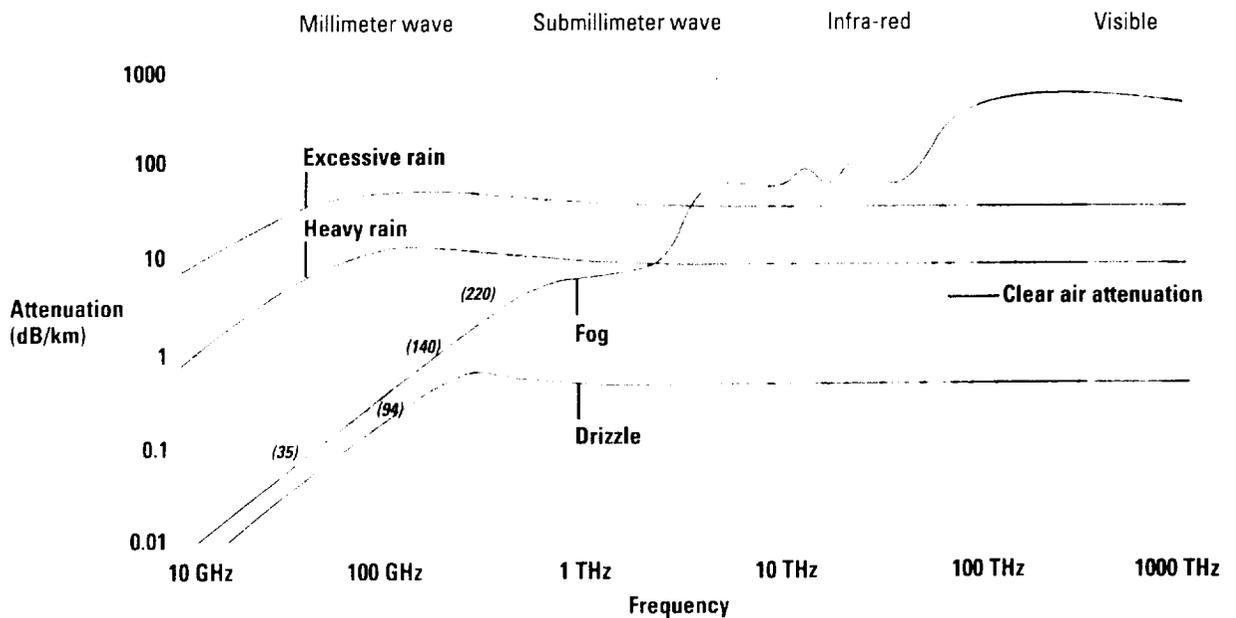
From the standpoint of technology, the time is ripe for millimeter-wave exploitation. At the Applied Technology Division, we have developed a strong phenomenology base for understanding millimeter waves through extensive field measurements and theoretical modeling. Current research in radiometry and interferometry includes such applications as oil-spill monitoring, atmospheric sensing, surveillance, and aircraft landing, as well as millimeter-wave component and subsystem development using superconducting electronics for quantum-efficient detection and low-noise operation.

We are developing millimeter-wave hardware systems. Our approach begins with identifying and defining the applications. System requirements are then specified based on mission needs using our end-to-end performance model. The model has been benchmarked against existing data bases and, where data is deficient, it is acquired via field measurements. The derived system requirements are then validated with the appropriate field measurements using our imaging testbeds and hardware breadboards. The result is a final system that satisfies all the requirements of the target mission.

Phenomenology

Atmospheric propagation. The usefulness of millimeter waves lies in the peculiarities of atmospheric attenuation phenomenologies over the prescribed frequency regime. Figure 2 shows the attenuation of electromagnetic signals in dB/km of propagation path-length from the microwave through the visible regime. This spans the frequency range from 10 GHz to 1,000 THz, with corresponding free-space wavelengths from 3 cm to 0.3 micron. Propagation of electromagnetic waves over this frequency range is subject to continuum

Figure 2. The attenuation of millimeter waves by atmospheric gases, rain, and fog.



as well as resonant absorption by various atmospheric constituents, including water (in both vapor and droplet form), oxygen, nitrogen, carbon dioxide, ozone, etc. In clear weather, IR and visible radiation propagates with little attenuation. However, water content in the atmosphere in the form of fog, clouds, and rain causes significant absorption and scattering. Conversely, in the millimeter-wave regime, there are propagation windows at 35, 94, 140, and 220 GHz, where the attenuation is relatively modest in both clear air and fog. Even taking into account the much higher blackbody radiation at the IR and the visible, millimeter waves give the strongest radiometric signals in fog when propagated over distances of interest. It is this ability that makes millimeter waves the best candidate for imaging in adverse weather.

While an imaging system benefits from the propagation window in the millimeter-wave regime, an atmospheric-sensing system uses the various molecular absorption lines. For example, the oxygen resonance line around 60 GHz (or 120 GHz) enables temperature-sounding in the atmosphere. Radiometric observations at a number of frequency channels around the oxygen resonance from a satellite platform can be used to unfold the vertical atmospheric temperature profile because atmospheric layers at various altitudes are 'sensed' with different observing frequencies. Essentially, the observed 'brightness' temperature is the result of superposing the radiometric contributions from various layers of oxygen in the atmosphere, less the attenuation of the electromagnetic energy by intervening layers as it propagates toward the observer. Pressure-broadening of the oxygen resonance and the variation of density and pressure with altitude give rise to weighting functions for the various altitude layers in their contribution to the measured brightness temperature at a given frequency in the neighborhood of the oxygen resonance. Similarly, the water-vapor absorption line around 180 GHz allows retrieval of atmospheric moisture profiles. Finally, atmospheric ozone can be monitored by observing the ozone absorption lines around 110 GHz.

Data interpretation and modeling. Figure 3 shows typical 94-GHz scene signatures from various surfaces at grazing incidence angle plotted as a function of polarization. The observed radiometric temperature of a scene is based on the following factors: emissions from scene constituents, reflections of the downwelling sky radiation by the scene, upwelling atmospheric emissions between the scene and observer, and propagation of the electromagnetic energy from the scene to the observer.

Figure 3. Measured grazing angle scene signatures at 94 GHz as a function of polarization and types of surfaces.

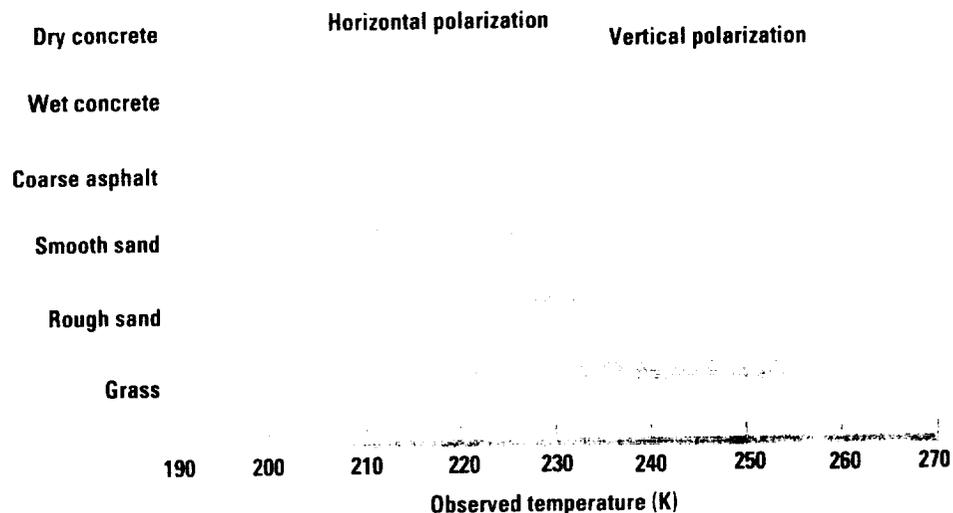




Figure 4. The airport scene on the left was acquired at 94 GHz with a TRW passive millimeter-wave field imaging system. The photo on the right is a visible image of the same scene.

The left-hand photo in Figure 4 shows a millimeter-wave image as measured by the TRW radiometric field imaging system; the right-hand photo shows a visible image of the same airport scene. In the radiometric image, the increasingly darker shades denote increasingly colder temperatures. Thus, the aircraft on the runway appears cold because parts of its metal surface, which is nearly perfectly reflecting, reflect the overhead sky, which is colder than the sky at the horizon. The asphalt runway, on the other hand, although also a good reflector at grazing incidence, reflects primarily the sky at the horizon, which is much hotter. The dirt adjacent to the runway is colder than the runway because the roughness of the dirt surface, although increasing its emissivity at grazing incidence, also mixes the reflections from various parts of the sky, effectively lowering the reflected sky temperature. One interesting feature that emerges from the image is the mirror image of the plane on the asphalt runway. This occurs because the asphalt runway, instead of reflecting the hot sky at the horizon, now sees a colder part of the sky overhead through reflections off the plane. Note that passive millimeter-wave images, unlike radar images, have a visual quality like IR and visible images.

We have developed a sophisticated end-to-end model with four components for the interpretation of millimeter-wave data and for the development of system requirements. The phenomenology model component includes models for the atmospheric propagation effects and meteorology; surface/terrain physics describing the mix of emission and scattering (based on bulk dielectric properties and surface/subsurface geometry) from scene constituents; ray-tracing algorithms for solution of the radiative transfer equation; and the use of combinatorial geometry for constructing complex scenes. Each aspect of the phenomenology model has been individually benchmarked against both measured data and other models in the literature. In addition, the phenomenology model as a whole has been benchmarked against the field imaging data that we have collected. The sensor model component includes the sensor optics, detector, and mechanical/electrical-effects models. It constructs realistic images as seen by the sensor, based on diffraction optics, and includes such effects as finite detector size and noise. The image-processing model component includes image-enhancement and image-restoration techniques. It takes as input raw data from the sensor and applies noise filtering, up-sampling (interpolation), temperature bandpass filtering, contrast

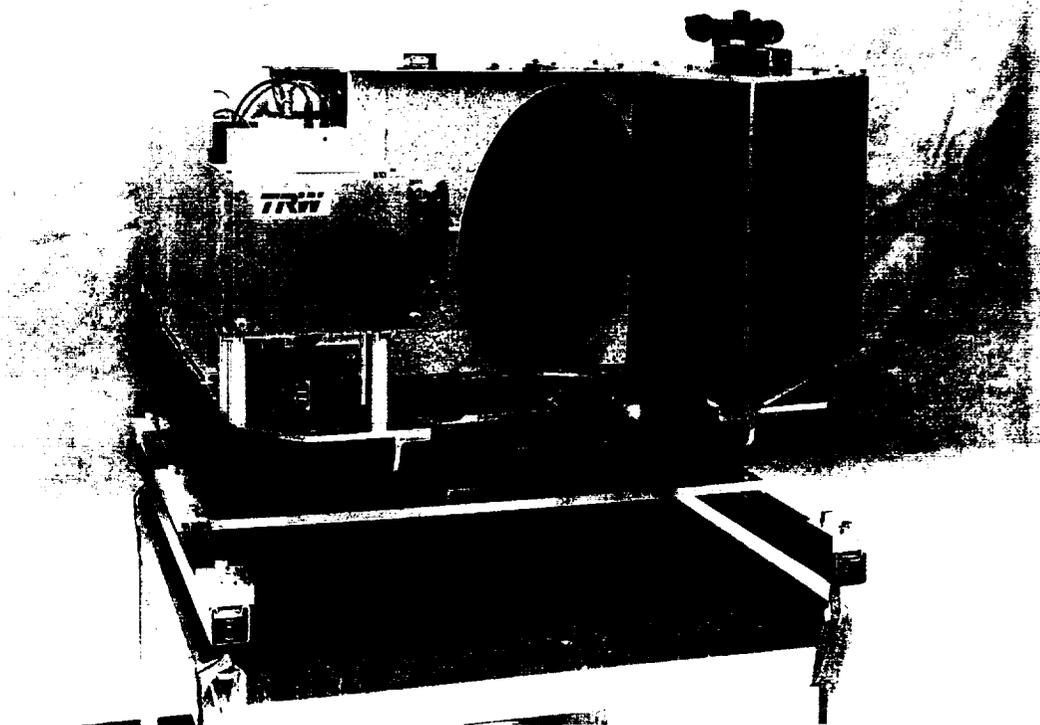


Figure 5. The TRW semiconductor-based multispectral radiometer has a 44-GHz detector channel and an integrated 94- and 140-GHz channel using a Gaussian optics lens antenna

enhancement, and edge-sharpening techniques to enhance the resulting image. Computer-aided symbology can be superposed on the image to facilitate display and image interpretation. Finally, the display model component captures the enhanced images, frame-by-frame, on video tape for replay at the frame-rate for which the images were produced. Various flight symbologies (heading, glide-slope, etc.) can also be incorporated in the images to simulate the complete scene a pilot might see on a heads-up display.

Laboratory and field imaging. We have developed multispectral radiometers to provide both ground- and flight-imaging capabilities. Flight and ground systems incorporating these radiometers have been built and used for technology demonstration and for acquisition of images under a variety of weather conditions. Advanced superconducting sensors and associated cryogenics have also been designed, fabricated, and demonstrated in a flight radiometer. For the exploration of high-resolution millimeter-wave imagery, a laboratory interferometer was built to assess sparse-array image collection with model scenes (see Technology Development, below).

The multispectral millimeter-wave imaging radiometers were developed using conventional semiconductor and superconducting detectors, low-noise signal conditioning electronics, microwave optics for imaging, computerized scene scanning, data acquisition, and image processing and enhancement. Our 'workhorse' semiconductor-based radiometer, shown in Figure 5, consists of a 44-GHz detector channel and an integrated 94- and 140-GHz channel using a Gaussian optics lens antenna. Flight capability for millimeter wave imaging has been demonstrated by acquiring flight radiometric images using a vibration-isolated, gyrostabilized platform that is mounted in a helicopter (Figure 6).

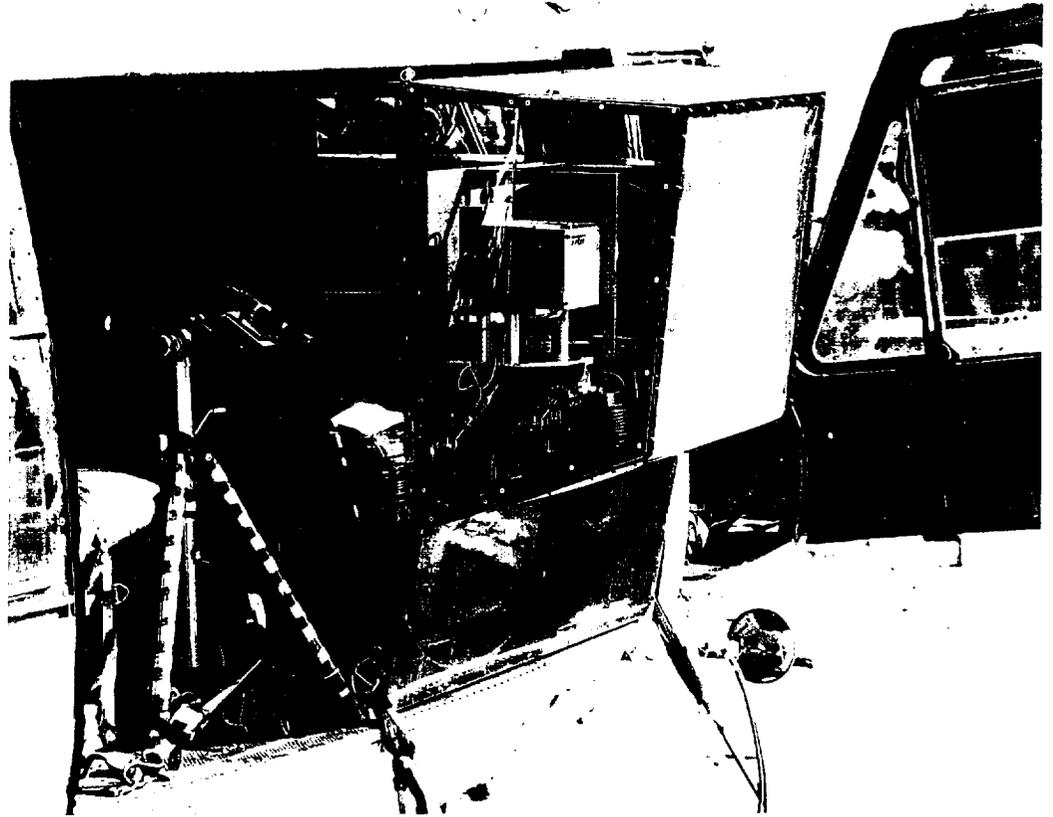


Figure 6 The vibration-isolated, gyrostabilized platform is mounted in a helicopter to give the radiometer flight capability

This instrument has successfully acquired images through clouds and at night, and has imaged special targets such as harbors, ships, boat wakes, refineries, airports, camouflaged vehicles, and oil spills (Figures 7 and 8). Buildings, ships, and rows of storage containers are visible in the harbor image. The oil spill images were obtained during the Huntington Beach, CA, oil spill of February 1990. An oil layer on the water is highly visible because it acts like an optical coating with varying thicknesses and resultant reflectivities.

Advanced microstrip integrated-circuit superconducting millimeter-wave video detectors for single- and multiple-frequency operation have been designed, fabricated, and tested. Our superconductor-based radiometer uses a two-dewar cryogenic system for separate 35- and 94-GHz tunneling-junction millimeter-wave detectors. This radiometer, like our semiconductor-based instrument, has flight capability using our gyrostabilized platform.

Extensive ground tests with our millimeter-wave radiometers have been conducted. Multi-frequency (44-, 94-, and 140-GHz) studies of imaging phenomenology were performed by measuring the polarization and view-angle dependent signatures of scene constituents. These include metal surfaces (bare and painted, under canvas, foliage, and camouflage), grass, water, asphalt, concrete, dirt, sand, gravel, and sky. Scenes of military interest containing vehicles in mixed terrain have been imaged with 3-meter resolution over several incidence angles from normal to near grazing.

To support the development of an aircraft landing system for use during low visibility, we have conducted a series of runway imaging tests with the



Figure 7. The top photo is a passive millimeter-wave image of the Long Beach, CA, harbor at 94 GHz. The photo on the right is a visible image of the same scene.

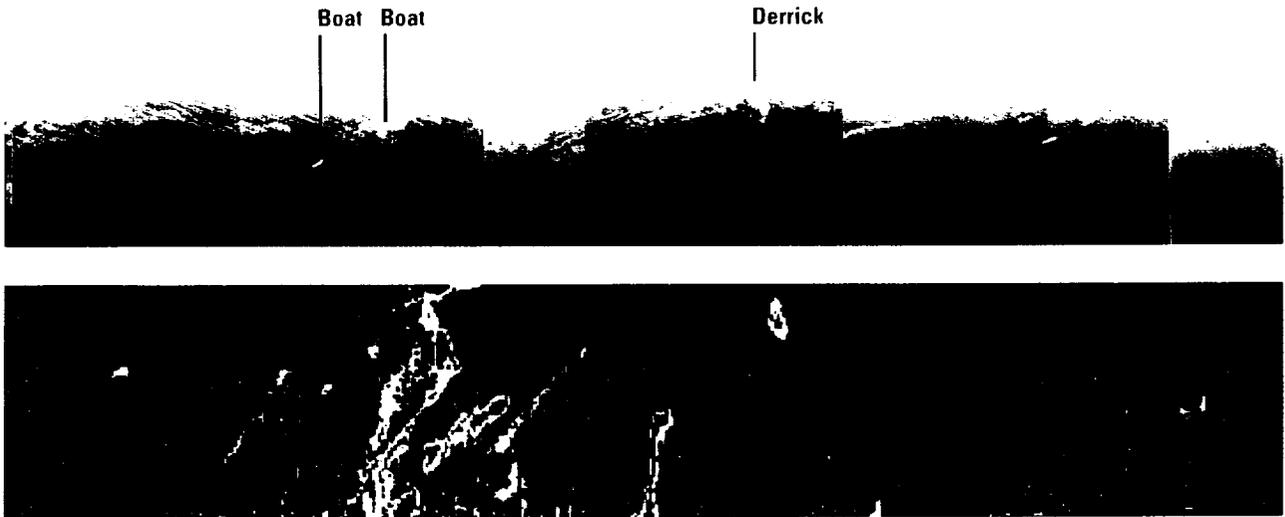


Figure 8. Passive millimeter-wave images of the February 1990 Huntington Beach, CA, oil spill

94 GHz radiometer, using 4-, 2-, and 1-ft-diameter antennas in fog (Figure 9), rain, and with snow on the ground. These field data serve to validate and benchmark our phenomenology model and define requirements for the aircraft landing augmentation sensor. The airport scene shown in Figure 4 was obtained with this field imaging system. For a potential shipboard navigation system, we have demonstrated the system by imaging a ship (the *Queen Mary*) across a harbor channel (Figure 10).

a.



b.



c.



d.



Figure 9 The results of 94-GHz radiometer runway imaging tests: a. and c. show visible images in clear and foggy weather; b. and d. show corresponding 94-GHz images

Technology Development

The demand for high image resolution drives system development toward high frequency systems. The millimeter-wave radiometric imaging system resolution is described by the 3 dB spot size of the receiver antenna given as $3\text{-dB spot} = 70^\circ \times \text{Wavelength/Size of optics}$. This equation expresses the fundamental relationship that millimeter-wave image resolution is inversely proportional to frequency and antenna size, and drives the trade-off involved in passive millimeter-wave imaging system development. The goal



Figure 10. The *Queen Mary* radiometrically imaged at a range of 1,700 ft across the Long Beach, CA, harbor channel at 94 GHz. The dome that covers the *Spruce Goose* appears in the background, left

is to develop ever-higher-frequency millimeter-wave hardware technology for finer image resolution with a given size optics, or to use higher-frequency hardware to maintain resolution while achieving the smaller and lighter system packaging that is crucial to many applications.

In step with this drive for higher-frequency millimeter-wave technology is the development of a practical system of utility within the bounds of hardware technology maturity and economics. Technology maturity includes sensitivity, compactness, and reliability; technology economics include system affordability, demand, and manufacturability.

Waveguide components and systems. The engineering of waveguide-type microwave component technologies is much better understood and in a more advanced stage of development than are its counterparts, the hybrid and the monolithic printed-circuit microwave components. As a result, development of passive millimeter-wave technologies usually begins with waveguide component building blocks that provide flexibility in design iterations and a much faster engineering process from design to breadboard. After the concept and system design are perfected, the breadboard is then turned into millimeter-wave hybrid systems or highly integrated, monolithic millimeter-wave prototype systems.

We have effectively used off-the-shelf millimeter-wave waveguide hardware to build field-measurement systems for phenomenology measurements, and have also produced numerous high-sensitivity waveguide components. Further development is under way in superconducting heterodyne mixers for higher signal detection sensitivity and in high-temperature superconducting millimeter-wave devices for simpler and more compact application systems.

The MMIC advantage. Innovation in millimeter-wave focal-plane array (FPA) design (see sidebar) using printed hybrid circuit technologies has led to the manufacture of 94-GHz millimeter-wave FPAs for passive imaging applications. Our 8-by-8-pixel passive millimeter-wave camera, built by Millitech Corp., has verified the design and maturity of the hybrid technol-

Imaging a two-dimensional scene with a single millimeter-wave detector is slow because of the large number of picture elements needed for a high-quality image and the per-picture element detector dwell-time needed to achieve the required sensitivity. When imaging a stationary scene, this slow process is acceptable; for a dynamic scene (from a moving vehicle, airborne platform, or satellite), time is simply not available because detector dwell-time will be very limited. A sensitive, high-density image can only be acquired with two-dimensional focal-plane arrays imaging in the video-frame mode or with line arrays imaging in the pushbroom mode.

Two-dimensional focal-plane arrays (FPAs) produce an image much like an everyday video camera that employs a visible FPA. Very high sensitivity in millimeter-wave imaging is achieved with each FPA element by staring at the scene of interest during the entire image acquisition time, instead of scanning through each picture element of the scene. The equation—Sensitivity (K) = Instrument noise temperature/(Bandwidth x Signal averaging time)^{1/2}—shows sensitivity is improved by a factor equal to the square root of the total number of focal-plane elements.

A line array acquires images in the pushbroom mode by mechanically scanning the line array in one dimension, or by mounting the line array on a moving platform and flying the platform over the scene of interest. For the same required number of picture elements, sensitivity is increased by a factor equal to the square root of the number of line-array elements over that which can be achieved by a single detector.

High-resolution images require high-density, tightly packed FPA elements mandated by the image-sampling theorem. The FPA element separation should be as close as possible to 0.5 wavelength. The challenge of implementing millimeter-wave imaging with FPAs resides in the hardware design: it must be a closely packed array of millimeter-wave receivers that is sensitive and is both RF and thermally stable.

In the past year, TRW funded Millitech Corp. to implement their patented breakthrough design that solves the close packaging and stability requirement for FPA fabrication at 94 GHz. This solution (Figure A) uses a combination of heterodyne receivers with an external, quasi-optically injected local oscillator and state-of-the-art, low-power, hybrid-component technology. Compact FPA thermal-loading issues are resolved by the separation of the local oscillator from the FPA assembly. The compact receiver design is made with millimeter-wave printed-circuit technology and with a design that has circuit elements extending from front to back. The receiver circuit component includes a printed antenna; a single-end microstrip mixer; a high-gain, low-noise IF ampli-

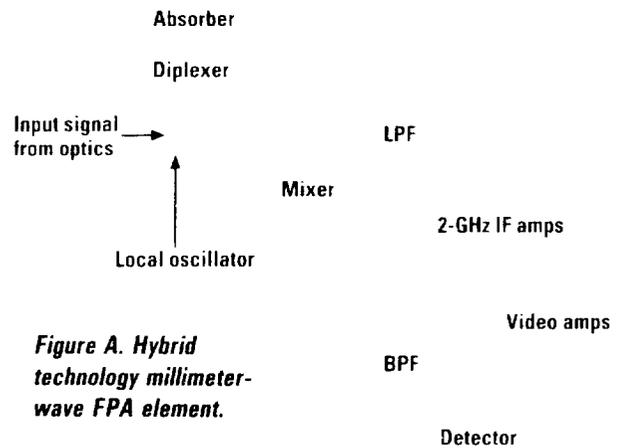


Figure A. Hybrid technology millimeter-wave FPA element.

fier chain with off-the-shelf MMICs; and signal conditioning and multiplexing circuits. The design also takes into account large-FPA manufacturability issues by integrating 8 FPA elements into a single subarray assembly with a single multiplexed signal output. It provides for automated assembly and ease of quality control, and forms the basic building block for large FPA assemblies.

With this 1-by-8-element subarray, a two-dimensional millimeter-wave FPA imaging system will then consist of a two-dimensional assembly of this subarray coupled to the local oscillator assembly; the imaging optics; and an image acquisition, analysis, and display system (Figure B). The TRW/Millitech team proved the maturity of this design and verified the technology's maturity for production-scale readiness. We built an 8-by-8-element, hybrid-technology, 94-GHz heterodyne detection FPA with a quasi-optical injected local oscillator. Provision for field-imaging demonstration was also implemented with 24-in.-diameter lens optics and an image acquisition and display system. The imaging quality of a large FPA was simulated by mosaic-image construction with the 8-by-8-element FPA. We are currently developing a 44- and 94-GHz pushbroom line-array imaging instrument. The line-array design will employ a side-by-side assembly of the 1-by-8-element subarray discussed above.

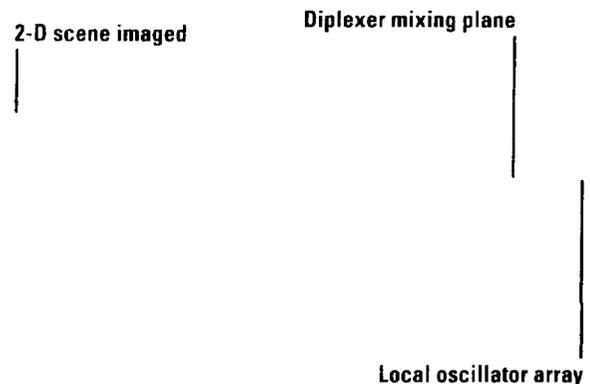


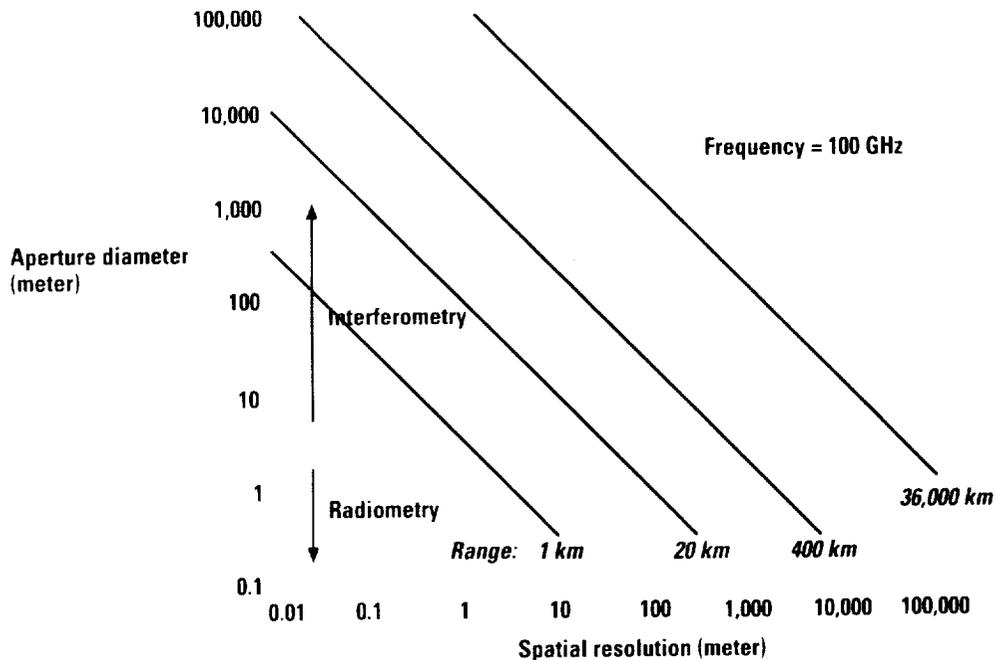
Figure B. Two-dimensional 94-GHz passive millimeter-wave imaging camera.

ogy involved. At the same time, our experience in the design and fabrication of the FPA revealed certain technology areas which, with improvement, would greatly enhance the reliability, manufacturability, and affordability of passive millimeter-wave FPAs. These areas include a highly integrated receiver circuit; an improved local oscillator injection diplexer design; improved local oscillator/receiver coupling to decrease local oscillator power requirements, which can result in a reduced thermal load and increased affordability; and system architecture improvement to decrease the number of functional blocks currently required, thereby improving manufacturability.

TRW's Microwave/Millimeter Wave Monolithic Integrated Circuit and IR&D programs recently produced advances in millimeter-wave amplifier and detector technology that can revolutionize passive millimeter-wave FPA design methodology and manufacturability. The recent millimeter-wave monolithic integrated circuit advances have led to the feasibility of simpler, lower-power-consumption, and more sensitive FPA designs. In the long run, as technology improvement leads to higher-yield monolithic-chip production, integration of many receiver millimeter-wave circuits into a single chip will further simplify the FPA circuit component count and the assembly process, and will result in a more economical final product. Ultimately, as the circuit reduces in size, a planar FPA design will become feasible and millimeter-wave FPA-on-a-chip will be a reality.

Figure 11. Apertures vary greatly with required resolution and range for low-altitude airborne, high-altitude airborne, low-Earth-orbit, and geosynchronous-Earth-orbit applications. Large aperture applications are enabled by interferometry.

Interferometry. A millimeter-wave laboratory interferometer was designed and built to demonstrate the concept of sparse-array interferometric imaging of terrestrial scenes and to evaluate the effectiveness of image-reconstruction schemes. Sparse-array aperture-synthesis techniques from radio astronomy permit the large apertures for high-resolution imaging (Figure 11). In aperture synthesis, also known as long- or very-long-baseline interferometry, the correlated output of antenna pairs sample the wavefront of scene emissions in an area known as the aperture. A two-dimensional inverse Fourier transform allows the scene image to be reconstructed with these samples. Image resolution is determined by the antenna spacing, rather than the physical size of



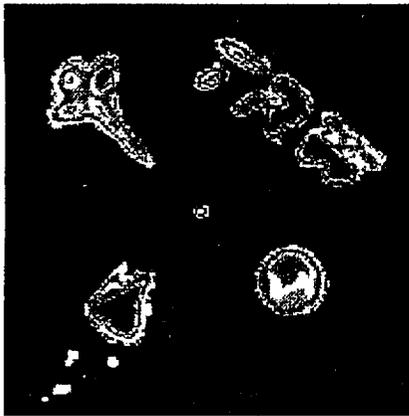
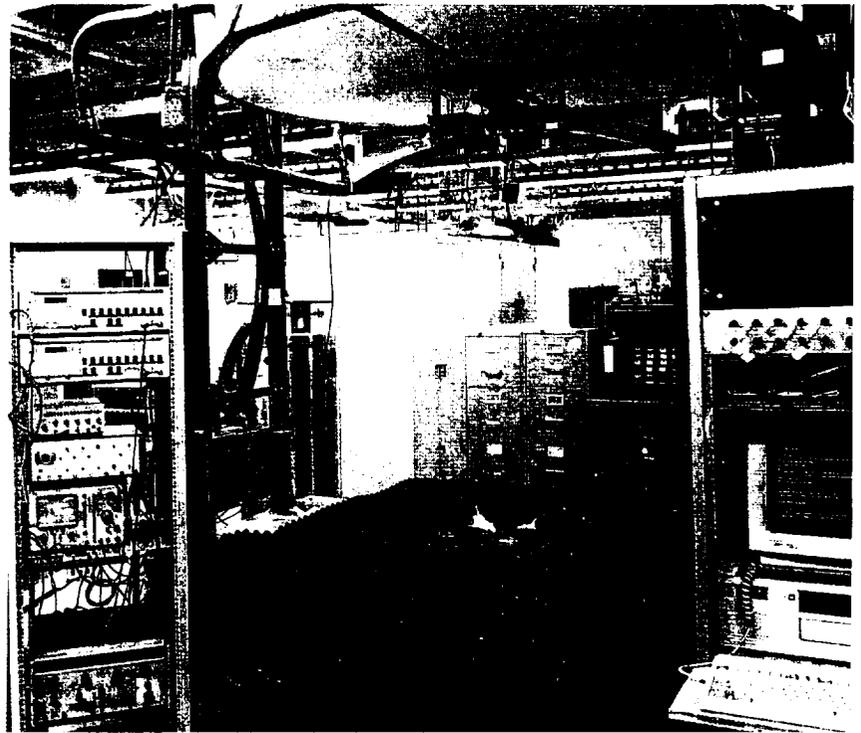


Figure 12. The photo on the right shows the high-resolution interferometer testbed facility. A model interferometer image is shown top left; the visible scene is shown bottom left



the antennas. This technique has been successfully employed in radio astronomy for high-resolution mapping of extra-terrestrial radio sources, and the resolution now exceeds that achieved by optical telescopes. The application of this technique to Earth observation is now of increasing interest. At TRW, we are investigating appropriate sampling and reconstruction methods.

Our interferometer testbed operates in several frequency bands and contains pairs of millimeter-wave radiometers, a positioning rail for baseline variation, elements of a simulated scene, data acquisition and display electronics, and a cryogenic model sky, the temperature of which can be controlled to simulate illumination conditions. The testbed and sample image data are shown in Figure 12.

Systems Applications

There are a multitude of applications that would benefit from a passive millimeter-wave imaging (PMMWI) system. PMMWI systems can be configured in various ways, depending on the application. A separation into one-dimensional, two-dimensional, and sparse-array designs distinguishes between three general system classes based not only on hardware complexity, but also on the missions to be achieved by each configuration. The first two designs improve the ability to acquire faster frames while keeping good radiometric sensitivity with longer integration times. In other words, they can produce higher-sensitivity images at faster frame rates. The sparse-array design improves the spatial resolution of the imaging, much as is done with high-resolution millimeter-wave radio astronomy.

One dimensional arrays are used for both fast and slower frame-imaging systems. When used on board a flying platform, a downlooking one-dimensional array is fixed to the aircraft in the cross-track position; the second dimension of the image is obtained by the aircraft motion along-track. The image

obtained is similar to the two-dimensional array image. Its line-scan rate is variable, depending on proper matching of aircraft speed and altitude with sensor aperture. One-dimensional array systems are also used on the ground and other fixed platforms requiring slower frame rates: the pushbroom array uses either mechanically scanned optics or is itself mechanically scanned.

Two-dimensional arrays are usually used when a PMMWI system requires imaging at frame rates similar to visual video cameras, i.e., between 10 and 30 Hz. It takes 5 minutes to obtain one frame of a 100-by-100-pixels image with a dwell time of 30 msec per pixel with a single receiver channel scanning the full 10,000 pixels. With a one-dimensional array of 100 pixels scanning vertically in a pushbroom fashion it takes 3 sec to obtain the frame; with a two-dimensional array staring at the scene it takes 30 msec to obtain the same frame. This latter choice has the distinct advantage of providing real-time imaging similar to visual and IR video cameras.

Finally an array farm, a distribution of either one- or two-dimensional multiple arrays with a baseline between each, forms a sparse array that can be used for high-resolution imaging. The technique is similar to radio astronomy and is employed in instances where a very large, solidly filled aperture cannot be implemented to support the required spatial resolution. The following paragraphs describe sample applications that show the utility of PMMWI systems.

PMMWI for the Landing Mission. The ability to take off, land, roll, and taxi in fog and low cloud ceilings has long been a high priority for both military and commercial aviation. Such capabilities hold high tactical military value as well as significant commercial gain for the airline industry. Attempts to achieve this mission have been made in the past, but none holds as much promise as millimeter-wave imaging, because it can be an autonomous method with the unique advantage of giving the pilot an image of the forward looking scene that he otherwise would not have in adverse weather. Equipped with a millimeter-wave sensor accidents caused by fog and low-visibility conditions, either in the air or on the ground, could be avoided.

Currently commercial jet aviation can land in low-visibility conditions (Cat III weather) only with planes equipped with an auto-pilot landing system and on runways equipped with two Instrument Landing Systems (ILSs), also called Category 2-type runways. In Cat III weather, the autopilot, using the double ILS electronic guidance, controls the hydraulic systems of the aircraft and brings it down on the runway automatically without the pilot being 'in the loop,' because he cannot see the forward-looking scene. Not only are these landings uncomfortable to pilots and limited to Category 2-equipped airports (and there are only thirty-five in the U. S.), but they are also not economical for the airline industry because of costs associated with tighter instrument tolerances, higher levels of equipment maintenance, and pilot training, as well as the limited availability of equipped aircraft/facilities.

The proposed concept for a pilot-in the loop, adverse weather system for take off and landing is a millimeter-wave sensor operating at any of the propagation windows of 35, 94, 140, or 220 GHz. Most of the currently proposed systems lie in the 35- or 94 GHz frequency windows because the millimeter-wave electronics hardware at these frequencies is both more mature and less expensive than at 140 or 220 GHz, and fog penetrability is greater.

In 1989, the Federal Aviation Administration, together with the Air Force, issued a program research and development announcement, called Synthetic Vision, to solicit bids for millimeter-wave sensors capable of carrying out the mission. TRW's PMMWI camera concept was one of the four winners selected for the first study phase.

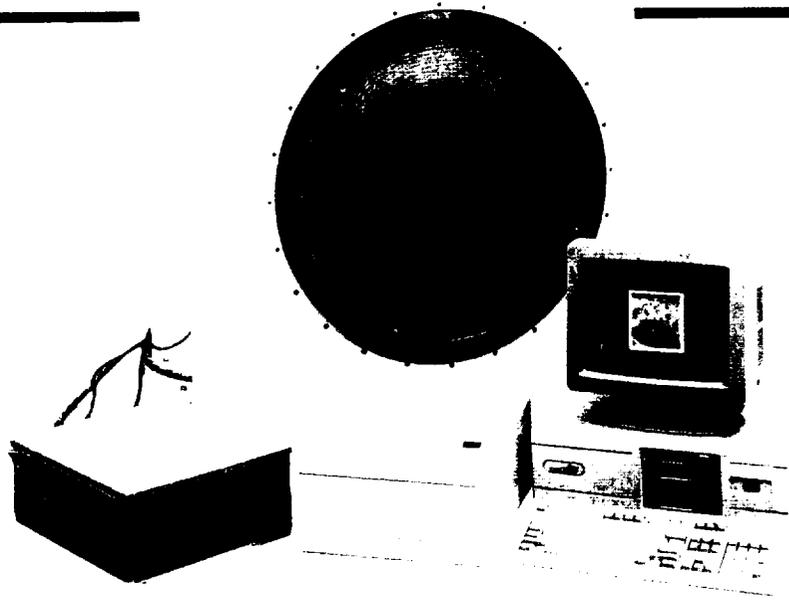
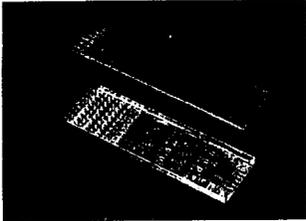
The civilian take-off and landing mission can be met with different types of millimeter-wave sensors. For the airline industry, both an autonomous and a beacon-aided system have been suggested. Some active systems use stored maps and a terrain-reconnaissance/terrain-mapping radar similar to those used in seeker missiles. Millimeter wave beacons can be used on the ground similar to landing lights at night. While both of these schemes are feasible when the landings occur on specific major airfields, generalizing the concepts to all airfields is almost impossible because of the high cost involved. General aviation, which is most of the non-airline part of the civilian sector, would not benefit from these systems. For example, air carriers of overnight delivery packages use many non-major airfields and such systems would be too expensive for them.

The TRW PMMWI system, however, has the unique capability of giving the pilot a literal, visual-like image of the forward-looking scene. It is autonomous in that it needs no ground assistance or other knowledge-based system; it can, if needed, operate with the assistance of ground-based beacons, an on-board flight-guidance system, or in conjunction with other imaging sensors such as IR or visual cameras. Thus, the TRW concept is a general one suitable for multiple users and missions. The TRW PMMWI video camera is designed to respond to all the requirements of the take-off and landing mission: operate in fog, low visibility, and adverse weather conditions; provide the pilot with a good resolution image of the forward-looking scene; provide adequate field-of-view for runway acquisition, landing, roll-out, and taxi; and provide real-time quality display of the acquired images.

The millimeter wave radiometric image is displayed to the pilot on a heads-up display that allows him to see through and recover the visual scene whenever fog subsides and visibility conditions improve during the landing. This gradual transition from millimeter-wave to visible image is only possible with radiometric sensors like passive millimeter wave and IR because of their visual-like image; active radars cannot provide this capability for the look angles required during landing and take-off. The TRW concept is a two-dimensional staring focal plane array, operating at the 94-GHz propagation window frequency, using a lens with a resolution < 6 milliradians, a field-of-view as large as 30° horizontal by 20° vertical, and an adjustable frame rate of 10 to 30 Hz. With an aperture resolution of 6 milliradians, the number of focal-plane-array receivers required to yield the full field-of-view is 80 by 56, or just under 5,000 receiver pixels. To prove the concept's feasibility, TRW and Millitech Corporation implemented an 8 by 8-pixels bread-board demonstration camera that performs most of the features of a large-array camera. Figure 13 shows the camera with its 24-in transmission optic lens and its PC-based data acquisition system.

Other applications. The TRW PMMWI sensor is the ideal sensor for many military missions. A major feature of the landing sensor is its covertness: it produces almost no emanations, which makes it highly desirable for military applications. We envision multiple applications for the PMMWI sensor and are working with the services to determine their specific requirements.

Figure 13 The photo on the right shows the TRW 8-x-8 pixel breadboard demonstration camera. The photo below shows the 8-pixel focal-plane array module.



Similar to visual and IR video cameras, the PMMWI video camera is a great asset for the surveillance mission. It can perform many of the missions that visual and IR cameras cannot perform during fog and poor-visibility conditions. While the price is usually decreased resolution, in many of the applications of interest the resolution is good enough for the detection of targets of interest. Some examples of these applications include ground surveillance of traffic in airports, at borders, at harbors and water channels, and on-board ships and armored vehicles. The camera can also be used for remote sensing, for Earth monitoring, and for ground or sea surveillance. In these applications, aperture synthesis may be needed, depending on the resolution required.

Millimeter wave radiometric images discriminate between various vegetation canopies, sand, concrete, asphalt, metals, ice, snow, and water. An air- or spaceborne sensor can also discriminate between different states of some materials: old and new ice, for example, coniferous trees with needle-like leaves and trees with flat leaves, dry and wet snow, and calm and agitated seas. The ability of millimeter-wave radiometry to discriminate between different fluids is useful in locating oil spills at sea, and in determining relative thickness and volume.

Sector Involvement

It is important to note that the technology and implementation of passive millimeter-wave imaging is not limited to the Applied Technology Division; there is a broad-based involvement by all the groups in the Space & Defense Sector. For example, many segments of the Space & Technology Group will be working on PMMWI sensors, sparse-array technology, space payloads and missions, and analyses and systems engineering efforts. Insertion of MMIC technologies in the sensor's hardware design and VHSIC technology for real-time image processing and display are tasks for the Electronic Systems Group. The Avionics & Surveillance Group is currently directing the aircraft landing mission and is chartered to implement airborne surveillance applications as well.

In all of these efforts, TRW's work—in the investigation of millimeter-wave phenomenology, the development of imaging systems, and the demonstration of systems—is enabling a whole new generation of low-cost, compact, imaging applications.

Recommended Reading

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**(Back row) Merit M. Shoucri, Larry Yujiri, Bruce Hauss, and Roger A. Davidheiser.
(Front row) Michael Mussetto, Stephan K. Young, and Paul S. C. Lee**

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